OPTICALLY MICRO-MANIPULATION OF MIE PARTICLES IN AN EVANESCENT FIELD OF A CHANNELED WAVEGUIDE

Takuo Tanaka and Sadahiko Yamamoto

Division of Advanced Electronics and Optical Science,
Graduate School of Engineering Science, Osaka University
1-3 Machikaneyama-cho, Toyonaka, Osaka, 560-8531, JAPAN
Phone: +81-6-6850-6307, Fax: +81-6-6850-6341
e-mail: tanaka@ee.es.osaka-u.ac.jp

Abstract

We report experimental results in which Mie particles were optically manipulated in an evanescent field generated in a multimode, channeled waveguide. Polystyrene spheres 4μm in diameter were trapped and were driven along the waveguide channel in an evanescent field of either fundamental or higher guided modes. When the multiple guided modes are excited simultaneously, the distribution of the meandering light's intensity is generated in the waveguide due to the coupling of the modes. The small particles are laterally trapped even in this meandering beat pattern and driven in a meandering fashion along the waveguide channels. We also made a waveguide whose channels are intersecting at right angles, and we optically changed the direction of the particles' movements at the crossing.

1. Introduction

In 1996 Kawata demonstrated a technique for driving both small dielectric and metallic particles by using the evanescent field generated in the vicinity of a single mode, channeled waveguide[1]. In our previous paper, we demonstrated optically driven Mie particles on multi-mode waveguides in which the small particles are optically propelled along the channeled waveguide using radiation pressure from the waveguide's either the fundamental or higher guided modes[2]. In this paper we report new experimental results regarding optically driven small particles in a meandering evanescent field which is produced by multiple modes' coupling, when the two or more guided modes are excited at a same time in the waveguide. In addition, we also report the experimental results in which we made a waveguide whose core channels are intersecting at right angles and we changed the driving direction of the particles optically at the crossing of the waveguides.

2. Experimental Setup

Figure 1 shows the schematic diagram of the experimental setup. We used polystyrene beads of 4.0 μm in diameter for the driven particles. The refractive index of the polystyrene bead is n = 1.59 and the specific gravity is 1.05 g/cm^3. The particles were dispersed randomly in purified water of index n = 1.33 and dripped on the channeled waveguide using spacers (made of microscope cover glass with a thickness of 170μm), and covered by another piece of cover glass (170 μm). Laser light (Nd:YLF, λ=1047nm) was fed onto the end-face of the waveguide using the end-fire method with a microscope objective of 20x magnification (NA = 0.4). Particles were observed using a microscope (40x magnification and NA = 0.55) and a CCD camera with IR-cut filter for cut-off the scattered laser light. The near-field pattern at the end-face of the waveguide was observed another microscope (20x magnification) and CCD camera. The power emanating from the waveguide was measured using a power meter.

We made straight, channeled waveguides on a glass surface using the thermal Ag^+ ion-exchange method. The cladding glass substrate (Crown glass) was immersed in molten $AgNO_3$ for ion-exchange. The temperature of $AgNO_3$ was 250°C during the process of ion-exchange, and the exchange time was 90 min. The width of the waveguides ranged from 4.0 to 18.0 μm at intervals of 1.0 μm, with a depth and length of 1.3μm and 2cm, respectively. The refractive index of the core was n=1.537 and that of glass substrate (cladding) was n=1.507. The waveguides whose core width is 4.0 μm to propagate the fundamental (E^x_{00}) and the first (E^x_{01})

modes, while the higher-order modes are cut off. (The mode number corresponds to the number of nodes (dark points) of the near-field patterns.) The waveguides whose core width is 18.0 μm can propagate up to the fifth (E^x_{05}) mode.

3. Experimental Results

Figure 2 shows an experimental result of the propulsion of small particles. In Figure 2, the width of the waveguide was 4.0μm. We excited only the fundamental mode in this waveguide. Figure 2 (a) shows a near-field pattern of the guided mode propagating in the waveguide and demonstrates that only the fundamental mode is excited and propagated. Figure 2 (b) displays the scattered light from the particles on the waveguide. Figure 2 (c) is a series of photographs of the particles taken at 3-s intervals. When the incident power was 800mW, the particles moved at a constant speed of 3.94μm/s over a total distance of more than 1cm. From Figure 2 (c), we found that only the particles localized on the waveguide channel are trapped on the center of the waveguide and are driven longitudinally along the direction of the waveguide channel, while particles outside the waveguide remained unmoved.

Figure 3 shows the experimental results. The width of the waveguide was 11.0μm, with this waveguide behaving as a multimode waveguide. Figures 3(a), (c), and (e) show the near-field pattern of the E^x_{01}, E^x_{02}, and E^x_{03} guided modes, respectively. Figure 3(b) shows a series of photographs taken at 5-s intervals, and (d) and (f) show photograph series taken at 6-s intervals. Figure 3 (b) indicated that the micro beads are transversely trapped at two positions which correspond to the high field-intensity region of the E^x_{01} mode, and they moved in a straight line, longitudinally. From this result, we confirmed that the radiation force attracts the particles laterally toward the high intensity region, and that the radiation force propels the particles toward the light propagation direction along the waveguide channel. As shown in Figures 3 (d) and (f), we could drive the particles along the waveguide by means of a higher guided mode as well.

Figure 4 shows other experimental results. We excited the multiple guided modes simultaneously in the same waveguide. When two or more guided modes are excited at the same time inside the waveguide, modes couple and interfere and then yield a beat because the propagation constants of each mode differ slightly from each other. This beat pattern meanders inside the waveguides. Figure 4 (a) shows the light streaks of the meandering beats. In this figure, two streak lines are observed crossing each other at the center of the photograph. Figure 4 (b) shows a series of photographs taken at 15-s intervals. This image is presented without the use of a IR-cut filter in order to reveal the streaked light and the scattered light. The driven particles are at the high light intensity position indicated by arrows. As shown in Figure 4 (c), the particles are trapped by this beat pattern and are driven meandering. These photographs are taken at 6-s intervals.

As shown in Figure 5 we made a waveguide whose core channels are intersecting at right angles and we fed the laser beam onto the both waveguides. Each laser beam is switched by a mechanical shutter. With using this setup, we drove the particles and changed the moving direction at the crossing of the waveguides. Figure 6 shows a series of photographs. While only the beam 1 is on, a particle moves down to the crossing ((a)-(c)). When the particle reached at the crossing, we switched the laser from beam 1 to beam 2, and then the direction of the particle movement was changed to the left ((d)-(f)).

4. Conclusion

We have demonstrated the experimental results of a technique for optically manipulating small particles along a multimode, channeled waveguide using radiation pressure caused by the waveguide's fundamental and the higher guided mode. The particles could be driven along the waveguide by trapping them on the waveguide channel even if the higher guided modes were used. We also demonstrated that by using the beat, the particles are trapped by the beat light and driven in a meandering fashion along the waveguide, and by using crossing waveguide, the direction of the particles' movements could be switched. A combination of these techniques with the techniques currently employed in optical integrated circuits, such as branching waveguides, optical switching devices, optical modulators, and so on, will be applicable to cell sorting, transporting, and mixing devices.

Acknowledgements

The authors are grateful to Professor S. Kawata and Dr. T. Sugiura for their valuable discussions and support of the experimental equipments.

References

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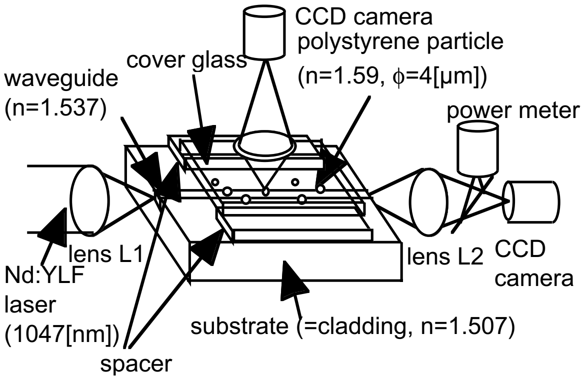


Figure 1

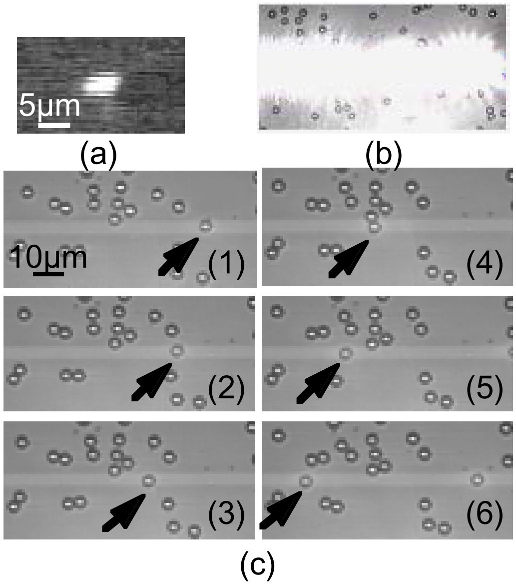


Figure 2

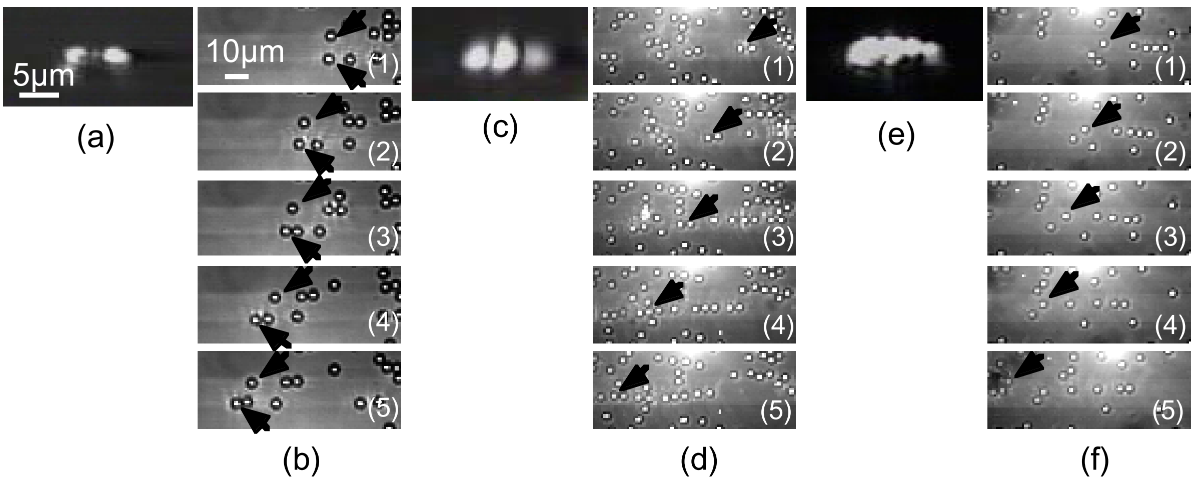
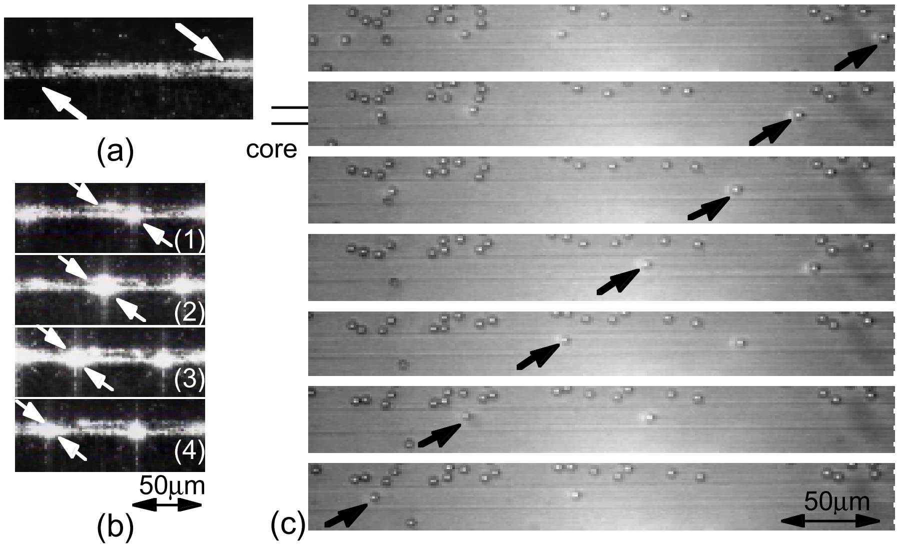


Figure 3



(a) (b) (c)

Figure 4

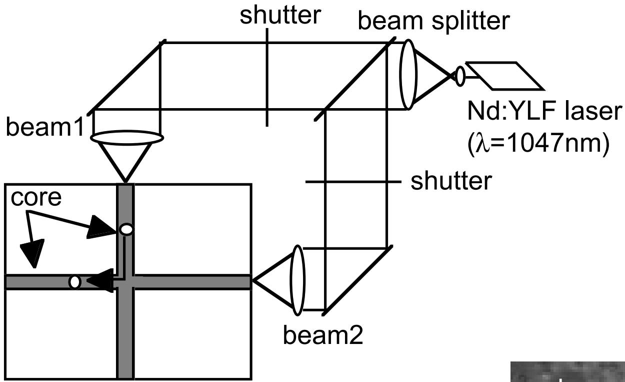
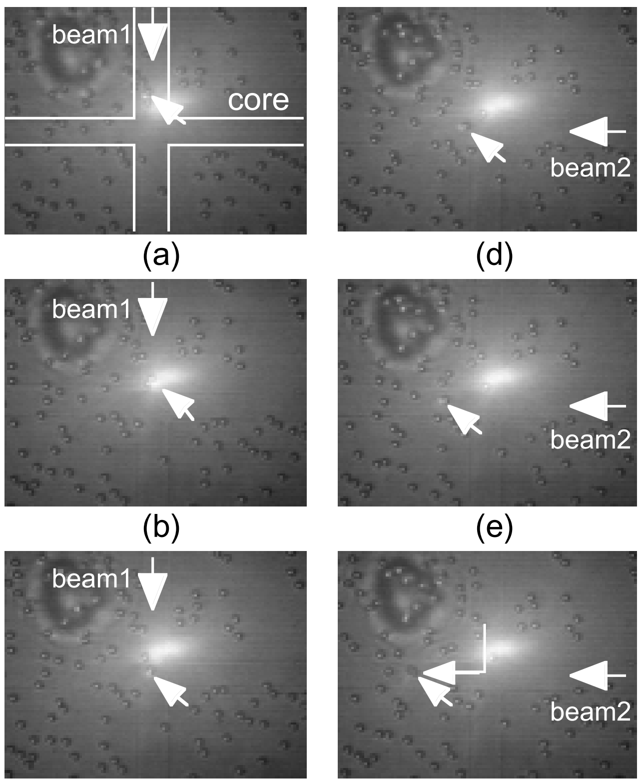


Figure 5



(a) (d) (b) (e) (c) (f)

Figure 6